

THE MARS 2020 LANDER VISION SYSTEM FIELD TEST

A. Johnson, N. Villaume, C. Umsted, A. Kourchians, D. Sternberg,
N. Trawny, Y. Cheng, E. Geipel, J. Montgomery*

The Mars 2020 Lander Vision System estimates position relative to an on-board map and provides this information to the spacecraft so that large hazards can be avoided during landing. The LVS is a new mission critical sensor and as such requires extensive validation. A field test conducted in May 2019 was the primary means to prove that the LVS will operate as designed. During this test over 600 independent real-time runs on engineering model LVS hardware and software were executed and clearly showed that it could meet a 40m position estimation requirement over a wide operational envelope. This paper will describe the test approach, operations and results. Specific examples as well as aggregate performance will be discussed along with off-nominal testing and fault recovery.

INTRODUCTION

The Lander Vision System (LVS) is a new sensor for Mars 2020 whose sole purpose is to estimate position relative to a map during EDL.¹ The LVS position is used by the spacecraft to target a nearby and safe landing site identified a-priori from orbital reconnaissance. Ultimately, this new Terrain Relative Navigation (TRN) capability has enabled the selection of the hazardous but scientifically compelling Jezero Crater as the Mars 2020 landing site².

The LVS consists of the LVS Camera (LCAM), the high-performance Vision Compute Element (VCE), Map Relative Localization (MRL) algorithms and VCE flight software. The LVS estimates position by fusing landmark matches between LCAM images and a map with inertial data that comes from the spacecraft Descent Inertial Measurement Unit (DIMU).

As shown in Figure 1, The driving requirements for the LVS are to reduce an initial 3.2km position error down to 40m and to do this in 10 seconds over all possible EDL conditions. These include altitudes from 4200m to 2000m, vertical velocities between 65 and 115 m/s and horizontal velocities up to 70 m/s. Attitude rates can be as high as 50°/s and off nadir angles up to 45°. Terrain properties are bounded by the slopes less than 15°, terrain relief less than 150m and image contrast greater than 6% (entropy > 4). Since landmarks are matched with image data, illumination conditions also matter. Sun elevations are 25° to 55° above the horizon and azimuths are between 240° and 310°. All of these environmental conditions introduce differences between the map image and the descent image that must be dealt with robustly during position estimation.

Terrain sensors for EDL are verified and validated (V&V) through a combination of simulation, hardware in the loop system testing and field testing. The advantage of field testing over the other methods is that it provides results from real-sensor measurements taken with engineering models of the flight hardware over real terrain with real illumination. Typically, the field test provides the

* NASA Jet Propulsion Laboratory, California Institute of Technology (4800 Oak Grove Drive, Pasadena CA 91109).

most trusted results for system performance and are consequently used to certify the simulation venue.

A captive carry helicopter field test of the LVS was conducted in May 2019. An engineering model LCAM and DIMU were mounted to a 2-axis gimbal that simulates parachute attitude dynamics. The VCE, with the VCE flight software, was inside the cabin of the helicopter and attached to support equipment that simulates the spacecraft interface to the LVS (see Figure 2) The LVS was operated exactly as it will be operated during EDL: an initial state estimate was provided to the VCE and thereafter the LVS performed real-time position estimation providing a correct and valid solution in under 10s. The resulting data products were retrieved from the VCE and the process was repeated. Flights were conducted at representative altitudes and the gimbal was operated with attitude rates and angles expected for Mars 2020 EDL. The test sites in the deserts of Southern California provided a wide variety of terrain types imaged under different illumination conditions.

There were multiple objectives for the test: (1) to perform end-to-end LVS processing in flight with real LCAM imagery at representative altitudes; (2) to perform a statistically significant number of real-time LVS position estimations in flight for comparison against simulation position estimates; (3) to collect synchronized LCAM, DIMU and ground truth data that span the LVS operational envelope for sensor model certification and off-line construction of data sets for simulation of large vertical motion; and (4) stress testing to execute real-time fault responses in the LVS and find the environmental conditions that could prevent position estimation.

This paper will describe the test design, specific results, the aggregate performance coverage of the operational envelope and the systems response to stressing conditions.

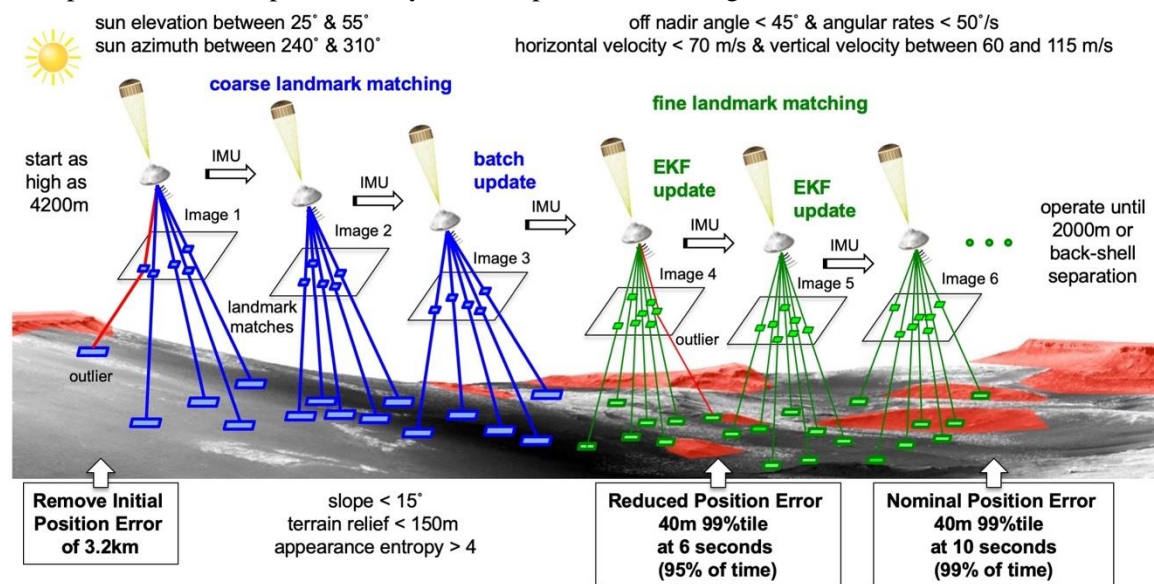


Figure 1. LVS Localization approach and operational envelope.

TEST DESIGN

The Mars 2020 LVS field test borrowed heavily from the previous technology demonstration of the prototype LVS conducted in 2014³.

System Under Test and Support Equipment

The LVS hardware and software was the system under test. This consisted of an Engineering Design Unit VCE, an engineering model LCAM, an engineering model DIMU and the VCE flight

software. As shown in Figure 2, the LCAM and DIMU were mounted on a two-axis gimbal attached to the front of a helicopter. The VCE was mounted within the cabin and was loaded with VCE flight software. The LCAM and DIMU provided data to the VCE using flight interfaces and rates.

Two racks of equipment inside the helicopter interfaced to the LVS and enabled test execution that was the same as flight. First, a power distribution unit converted 28V/80A helicopter power to the various voltages required to operate the VCE (LCAM is powered by VCE), DIMU and support avionics. The support avionics included a commercial GPS/INS for helicopter state (from Applanix), a processor that provided real-time gimbal states (SCSIM) by fusing gimbal encoder measurements with position, velocity and attitude from the Applanix, and a processor that implemented the flight 1553 and high speed serial interfaces to the VCE (GSERT). All of these processors were accessible through an operator console. SCSIM had dual purposes: first, it provided ground truth estimates of position velocity and attitude that can be compared to the ones computed by LVS, and, second, it provided the estimate of spacecraft state required to initialize the LVS processing. In the second case, flight like biases and random noises were added to the estimates by SCSIM before being sent on to LVS.

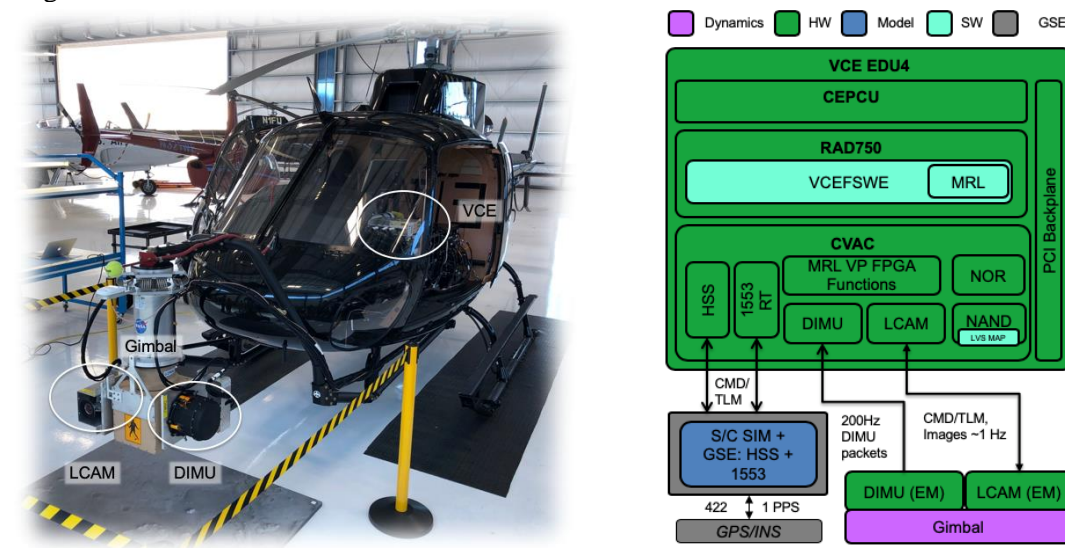


Figure 2. Field test vehicle and payload.

Vehicle and Flight Profiles

Although the LVS operates during parachute descent, multiple studies have shown that vertical motion is not a performance driver.⁴ What is more important to obtain from the field test is real-time LVS results with the real LCAM over a wide variety of imaging conditions. Therefore, even though it cannot come close to parachute descent speeds, a helicopter was selected as the field test platform because it can quickly change altitude and direction which allowed testing from different points of view throughout the test site.

After a flight test to prove that the vehicle could achieve 5000m MSL (4200m AGL + 800m test site altitudes), an A-Star 350 helicopter was selected for the test. The helicopter has a certified mounting structure for the field test gimbal and sufficient power and cabin volume for the LVS payload racks and operator. The helicopter can achieve 60 m/s horizontal airspeed and +/- 1.5 m/s vertical speed.

The purpose of the gimbal is to model the attitude dynamics during parachute descent subject to the constraints given in Table 1. First, bounding attitude trajectories were generated by the POST simulation of Mars 2020. The trajectories were processed to extract statistics on off-nadir angle,

attitude rates and frequency and amplitude of oscillations. These defined the space of possible attitude profiles. Thirteen azimuth and elevation profiles that could be implemented by the gimbal were manually constructed to span this space. As shown in Figure 3, the off-nadir angle and angular rate space is well covered by the gimbal profiles.

Table 1: Gimbal limits

	Min angle	Max angle	Min rate	Max rate	Min accel	Max accel
elevation	-20	80	-60	60	-120	120
azimuth	-50	50	-100	100	-200	200

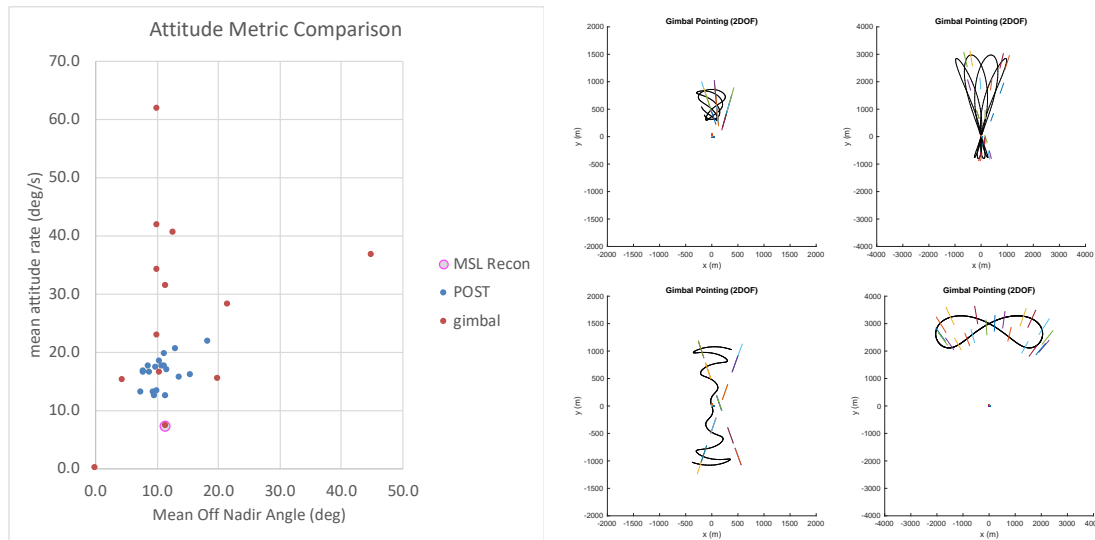


Figure 3. (left) Gimbal profiles span the off nadir angles and attitude rates expected from simulations (POST) and the MSL flight reconstruction. (right) representative trajectories of the gimbal boresight at 4200m.

Two types of flight profiles were conducted. The most common profile flew around the entire LVS map in order to obtain as much terrain coverage as possible. This profile was called the “Figure 8” because in each loop the helicopter would switch direction to prevent GPS wind up (See Figure 4). These profiles were executed by programming a sequence of waypoints in to the helicopter auto-pilot. Simultaneous to the flight profile the gimbal profiles were changed manually on a regular basis to ensure adequate coverage of the attitude space.

The second profile, called “Spiral” in Figure 4, had the helicopter fly over a single way point starting at the lowest altitude and with each pass increasing the altitude by 100m. LVS was operated when passing through the waypoint and in post processing the images collected over altitude were stitched together with synthetic DIMU data to simulate vertical descent.

Test Sites, Illumination, and Maps

The Jezero Crater landing site has 80m high cliffs, craters, dune fields, boulder fields, mesas and hills. The field test sites should ideally contain these types of terrain features while being free of man-made objects and trees across the 30km x 30km LVS map. The sites should also have elevations lower than 800m, so that the helicopter can reach the 4200m AGL, and be close to an airport for test operations.

Three test sites in the Mojave National Preserve accessible from the Baker, CA airport were selected. These sites were all close to the 800m elevation limit but had a wide variety of Mars like terrain. Hole in the Wall (HIW) contains 300m high cliffs around a mesa, Desert lava Tubes (DLT)

has numerous lava flows and cinder cones similar to craters, while Kelso Sand Dunes (KSD) has a large dune field similar to the fields of inescapable hazards in Jezero Crater.

The second set of three sites were in Death Valley National park accessible from the Furnace Creek airport. These sites are near sea level so they allowed testing at altitudes above 4200m AGL. Badwater (BDW) contains low contrast salt flats and boulder fields, Mesquite Flats (MSF) contains a small dune field and steep but bland slopes, and Panamint Valley (PNV) contains very high terrain relief near bland desert terrain.

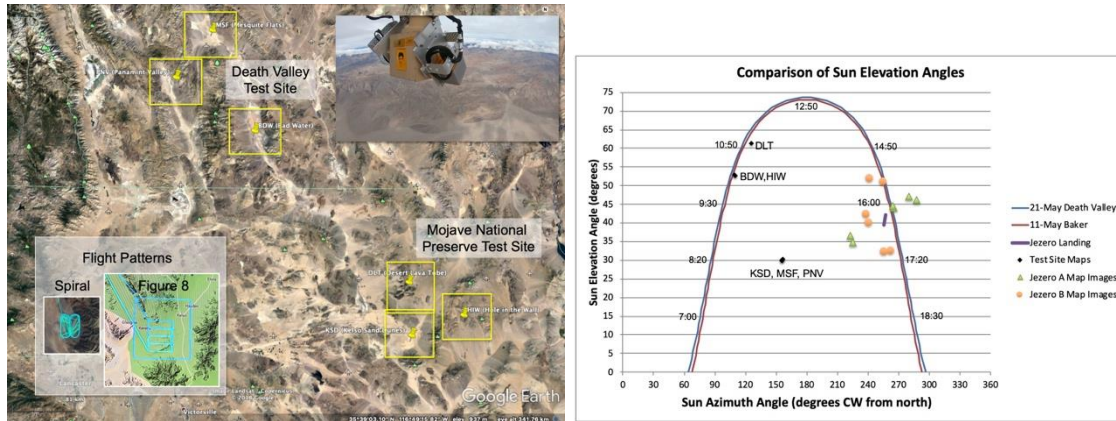


Figure 4. (left) Test sites and flight profiles. (right) Illumination angles for field test and flight.

30km x 30km maps at 6m/pixel were made for each of these six sites. The elevation data was interpolated from 10m/pixel digital elevation maps (DEM)s generated from the TanDEM-X and TerraSAR-X (European radar missions). The imagery was ordered from Planet Labs Inc. Multiple images at 3.5m/pixel were required for each map and these were stitched together using similar techniques used for generating the Jezero Crater flight map. All of the Planet Labs images were taken at 10am but at different times of year.

Figure 4 shows the solar azimuth and elevation angles for the test window (red and blue curves), the imagery used to make the field test maps (black diamonds), the imagery used to make the Jezero Crater flight maps (orange disks and green triangles) and the LCAM illumination conditions throughout the landing window (purple line). The flight maps are made from MRO-CTX imagery which always takes images at 3pm. Landing is around 3pm so that MRO can be used as a telecom relay. The CTX images are also selected to be in the same season (northern spring) as landing, so the illumination conditions for the flight maps and LCAM images will be very similar.

During the field test, the LCAM and map images will have similar illuminations at specific times of day for specific maps but not most of the day and not for all of the maps. The field test map images are taken at 10am. The maps for DLT, BDW, and HIW were taken a few days before the field test started, so, around 10am, the LCAM and map illumination conditions were similar. This is indicated by the black diamonds for DLT, BDW, and HIW near the blue and red curves in Figure 4. However, the map images for KSD, MSF and PNV were taken in November 2018 which caused significant differences from the field test LCAM images no matter what time of day it was. Because field test operations are expensive, the helicopter typically flew twice a day, and this resulted in large differences in illumination conditions during testing. As described below, the LVS performed very across a wide range of illumination conditions.

TEST OPERATIONS

Between May 14th and May 24th, 2019, a total of 17 helicopter flights were conducted with 656 total executions of the LVS position estimation process (called a run). Table 2 gives a summary of the flights. Figure 5 shows histograms of the coverage of the flight operational envelope; the red bounds indicate the flight operational environment. The maximum 70 m/s horizontal velocity was covered by a few passes downwind at maximum horizontal wind speed. The altitude range was easily covered and exceeded on the low and high ends. Many of the gimbal profiles were flight like with an off-nadir angle near 20° but some profiles went above the 45° requirement. Similarly, the angular rates were centered around flight nominal but in some cases profiles exceeded 90°/s. Entropy is a measure of the contrast in the scene; the test sites went beyond the operational envelope into very bland scenes not expected at Jezero Crater (e.g., the valley floors of Panamint Valley and Badwater). LCAM to Map delta sun angle is the angle between the vector to the sun when the LCAM image is taken and when the map imagery was taken. For Mars 2020 this angle is less than 20°, but in the field test, angles up to 120° were encountered. Terrain slope and terrain relief are defined over 1500m x 1500m area which is the size of the landmarks matched during the coarse phase. Terrain slope is the best fit plane to a patch 1500m on a side while terrain relief is the 99%tile residual from this plane. The 15° and 150m thresholds for these parameters were frequently exceeded in the field test results.

Table 2. Flight Summary

Site	# Flights	# Runs			Notes
		nominal	coarse retry	total	
KSD (Kelso Sand Dunes)	3	94	6	100	
HIW (Hole in the Wall)	1	47	0	47	
DLT (Desert Lava Tubes)	2	76	1	77	1 30s duration
BDW (Badwater)	6	211	8	219	1 spiral
PNV (Panamint Valley)	1	41	3	44	
MSF (Mesquite Flats)	4	167	2	169	1 spiral, 1 30s duration
Total	17	636	20	656	

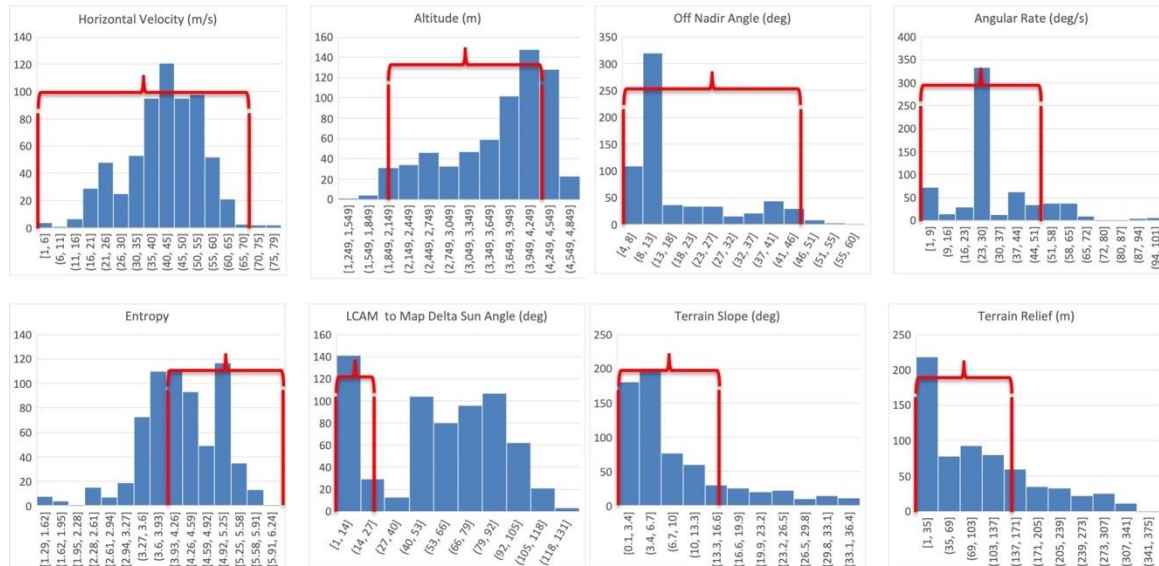


Figure 5. Histograms showing coverage of flight operational envelope.

TEST RESULTS

First, some illustrative runs will be discussed. This will be followed by the aggregate performance for runs within the operational envelope, within an expanded envelope and then all the runs. Next, vertical motion results generated from one of the spiral flights will be given and, finally, runs that were so challenging they required a retry of the landmark matching will be discussed.

Example Results

The first row of Figure 6 shows an example set of landmark matches for the first coarse image and last fine image from one of the runs over the “Hole In the Wall” test site. In each result, the LCAM image is shown in the top right and the location of the image footprint in the 30km x 30km map is shown in the bottom right. A zoom in on the matches in the map is shown on the left. Correct landmark matches between the image and the map are shown in green while the other colors denote outliers thrown out by the processing. Due to 300m cliffs in the image, this run is outside the LVS operational envelope, but LVS still succeeded in estimating the spacecraft position (second row). LVS also estimated attitude and velocity, but, because of the short duration of this run, these are still converging (third row). The fourth row shows the state of all the landmark matches. There are close to 100 IP_REJECT_OK landmarks which are the inliers that are used to estimate state. The rest of the 150 landmarks are outliers rejected during processing.

Figure 7 shows a 30s duration run over the DLT map. The attitude rates and off nadir angles are high for this run, but it still matches over 100 landmarks and generates accurate position, velocity and attitude estimates. In fact, for this run, there are so many inliers that some of them have to be thrown away (IP_REJECT_EXCESS_LANDMARK) before being sent to the estimator.

Aggregate Results

Figure 8 shows horizontal position error scatter plots and number of inlier landmark matches versus total horizontal error for three groupings of the field test runs: within the flight operational envelope, an expanded envelope to bring in more runs and all of the runs. These results are taken at the epoch 10s from the start of the exposure of the first image used. In that time interval the LVS will process 3 coarse images and 4 fine images generating at most 415 inlier landmark matches.

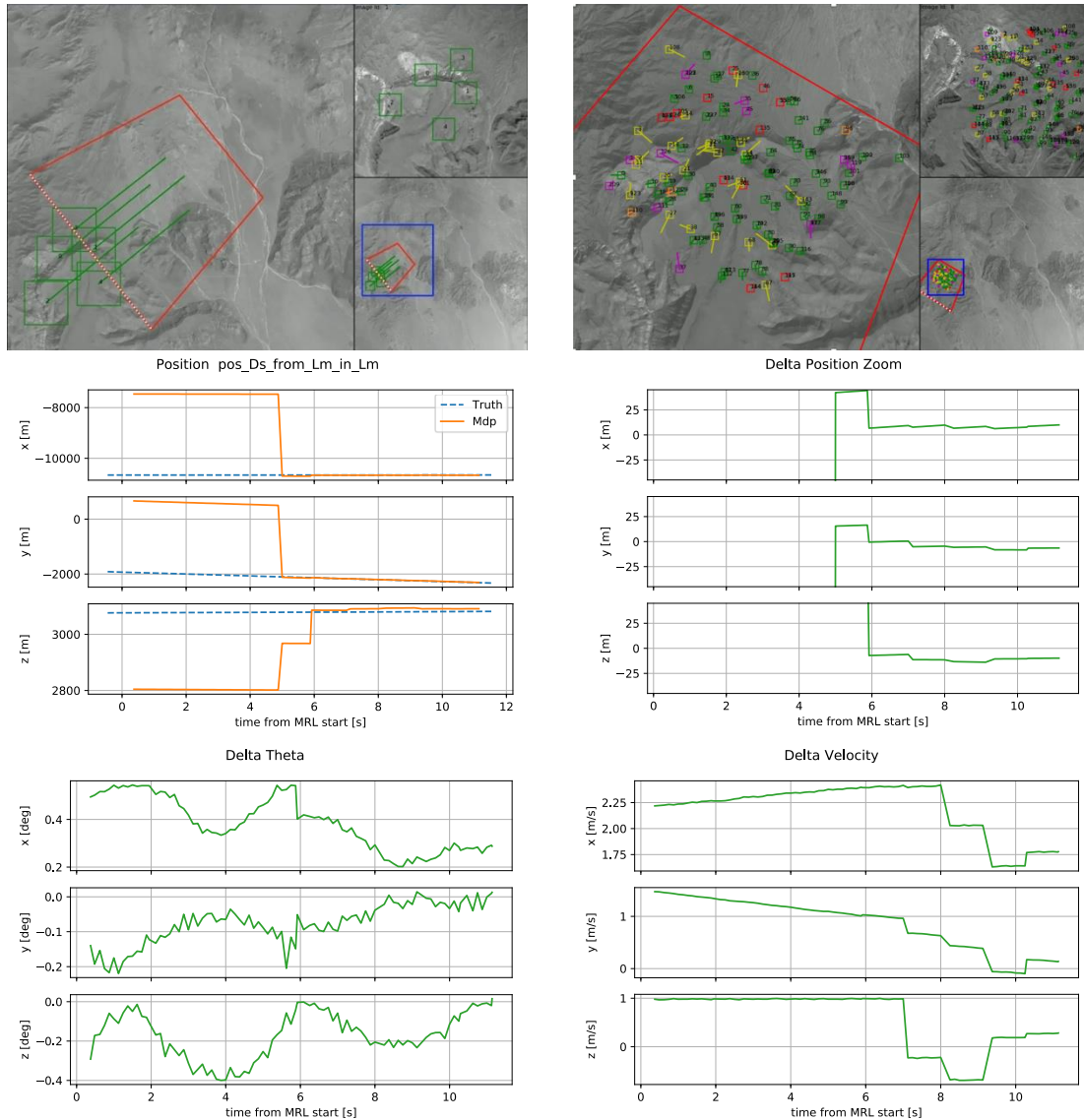
Because of the fairly tight constraints on the operational envelope relative to what was encountered in the field test, only 83 out of 656 runs were in the flight operational envelope (top row of Figure 8). As shown in the top row of Figure 8, the horizontal position errors easily meet the 40m requirement. Almost all the runs have close to the maximum number of landmark match inliers. The run with the lowest count had a large cloud shadow in the images that prevented correct matching of some of the landmarks. Even in this case, which will not happen on Mars, the number of fine landmarks was near 70 per image which is more than necessary to estimate an accurate position.

The operational envelope was expanded to let in more runs and increase the statistical significance of the results. This expanded envelope decreased the minimum allowable entropy from 4 to 3, letting in more bland scenes. The largest change was to increase the delta sun angle between the LCAM and map images from 20° to 100°. There is no reason this delta angle constraint will be violated during landing, but increasing it allows the use of afternoon flights for performance assessment. The expanded envelope also increased the maximum altitude from 4200m to 5000m and the angular rate from 50°/s to 100°/s. The middle row in Figure 8 shows that all of these 393 runs still meet the 40m position error requirement. There are some runs that have a low number of inlier landmark matches which is expected when allowing scenes with significantly different illumination conditions.

The final aggregate result is for all field test runs. This set adds cases to the expanded set with extreme terrain relief and slopes, very large differences in illumination angles and large off nadir angles. As shown in the bottom row of Figure 8, only 7 of the additional 263 runs have position

errors that are outside the 40m requirement. All 6 of these are from a KSD run in the late afternoon that had delta sun angles greater than 100° .

Table 4 compares the results for each grouping to the flight requirements at various epochs. The position estimate should be less than 200m at the end of the coarse phase to initialize the local spatial correlation used during the fine matching phase; this requirement is met for all groupings. In the off-nominal situation where the EDL timeline has been dramatically compressed, the LVS should attempt to report a position estimate at 6s based on the first fine image; this requirement is met for the flight and expanded envelopes. For completeness the performance at 10s is also shown.



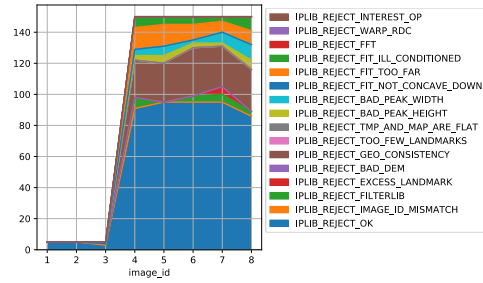


Figure 6. Example 10s LVS run at HIW over 300m cliffs. (HIW_01_MRL_1558113473_run003)

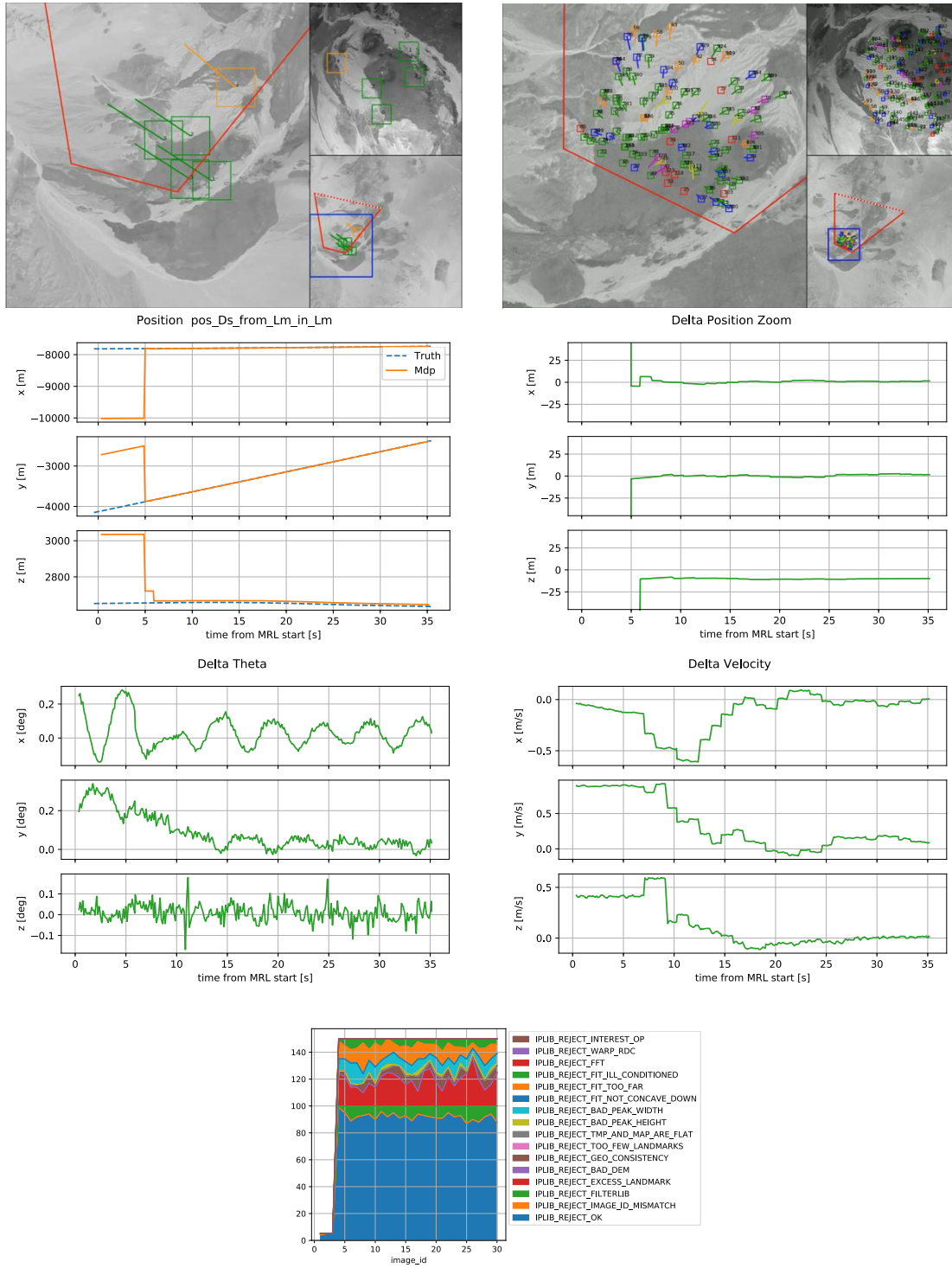


Figure 7. Example 30s LVS run at DLT showing convergence of attitude and velocity (DLT_02_MRL_1558713867_run014)

Table 3. Groupings for the aggregate field test runs.

Metric	Flight Envelope		Expanded Envelope		Test Coverage		# Runs Outside Flight Envelope
	Min	Max	Min	Max	Min	Max	
Image Entropy	4		3		1	7	257
Terrain Relief (m)	0	150	0	150	0	373	153
Terrain Slope (°)	0	15	0	15	0	35	120
Delta Sun Angle (°)	0	20	0	100	1	121	572
Horizontal Speed (m/s)	0	70	0	70	0	77	4
TRN Altitudes (m)	2000	4200	2000	5000	1163	4740	26,194
Boresight OffNadir Angle (°)	0	45	0	45	0	56	18
Angular Rate (°/s)	0	50	0	100	0	99	101
Number of Runs	83		393		656		

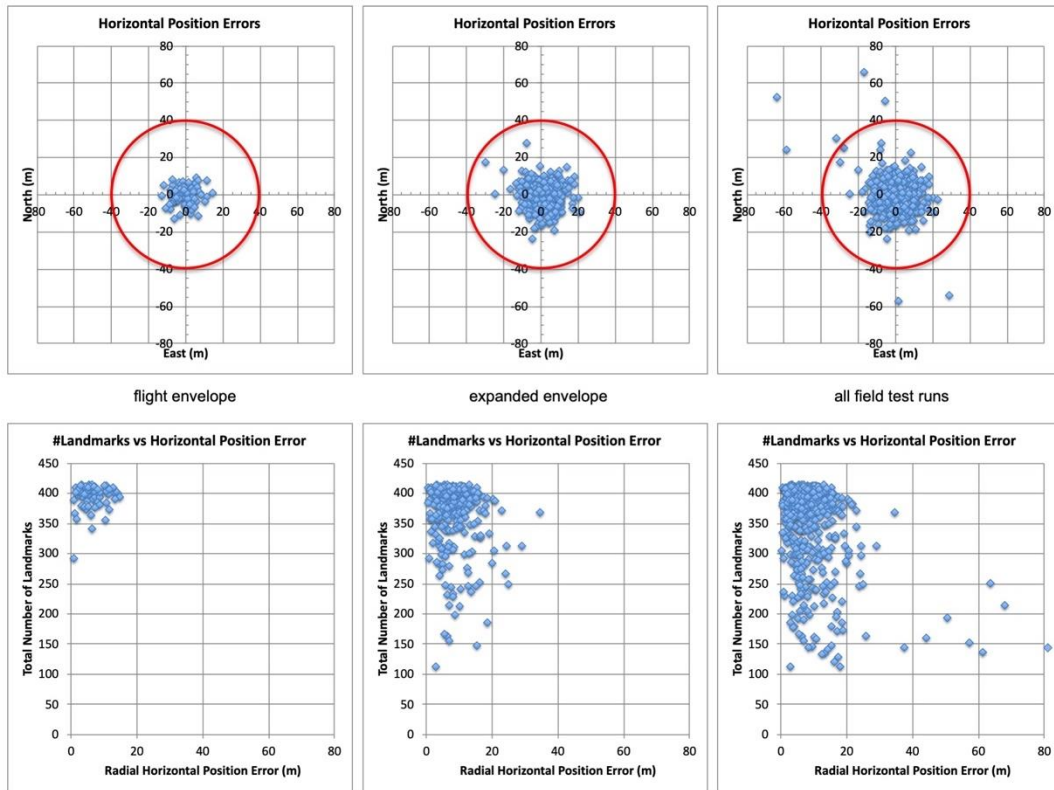


Figure 8. Horizontal position error scatter plots and horizontal position error versus number of inlier landmarks for the flight envelope, expanded envelope and all field test runs. The 40m requirement is shown as a red circle.

Table 4. Horizontal Position Estimation Statistics

99%tile Radial Horizontal Position Error	Flight Operational Envelope	Expanded Operational Envelope	All Field Test Runs	Requirement
End of coarse	158.0m	135.3m	169.3m	200m
At 6s	16.0	30.5m	44.5m	40m
At 10s	14.3	24.3m	55.4m	40m
number of runs	83	393	656	

Vertical Descent Results

One of the flights at Badwater and one at Mesquite Flats followed the spiral test profile. Images were taken from 2000m to above 4200m altitude in increments of roughly 100m. An image was selected from each run so that the motion profile was close to vertical (see Figure 9 top left). The ground truth position and attitude were extracted to generate a vertical trajectory. This trajectory was run through a simulation model to generate synthetic DIMU data. The images, IMU data and a spacecraft initialization packet were then input into the LVS hardware by the LVS GSE and processed. The position estimation errors are less than 5m throughout the descent (see Figure 9 top right). A landmark matching result from the top and bottom of the descent are shown in the bottom row of Figure 9.

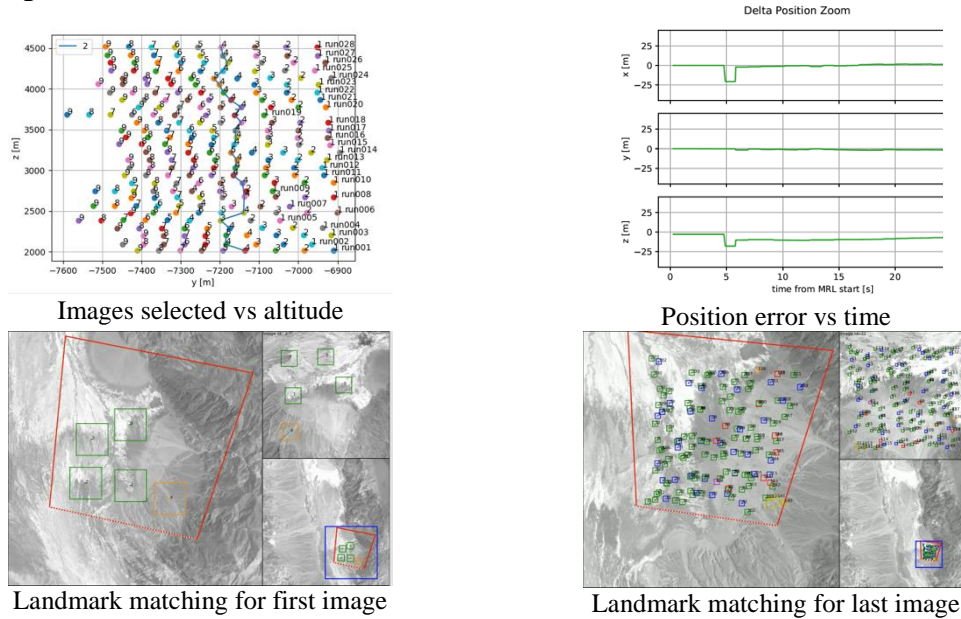


Figure 9. Vertical descent results for the Badwater sequence

Off Nominal Results

“Coarse retry” is a second chance to estimate position from images assuming there is something intermittently wrong with the LCAM image that prevents matching. If there are less than 3 landmarks matches total in coarse or less than 20 landmarks per image in the initial fine phase then the VCEFWE will perform a coarse retry. Coarse retry restarts the processing chain: a new spacecraft initialization packet will be acquired, then coarse image processing, fine image processing and estimation process will be repeated. During flight, the number of coarse retries is limited to one before more extreme fault protection occurs, but in the field test the number of coarse retries was allowed to be much larger.

During the field test there were 20 runs that resulted in at least one coarse retry. None of the runs were in the operational envelope; the reasons are tabulated in Table 5. Figure 10 show the

number of landmark match inliers for a run in Panamint Valley. The run started over very high terrain relief imaged under illumination condition that were quite different from the map (delta sun angle of 57° , terrain slope of 23° and terrain relief of 281m). On the fifth application of coarse (4th coarse retry), the helicopter had flown farther into the valley where the terrain relief was not as extreme, and the fine mode was able to continue successfully. The final position error for this run was less than 10m.

Table 5. Summary of coarse retries.

Primary reason for coarse retry	Count
Clouds or cloud shadows in images	5
Large terrain relief and illumination differences	3
Extreme illumination differences	7
Saturation	3
Large terrain relief	1
Edge of map	1
Total	20

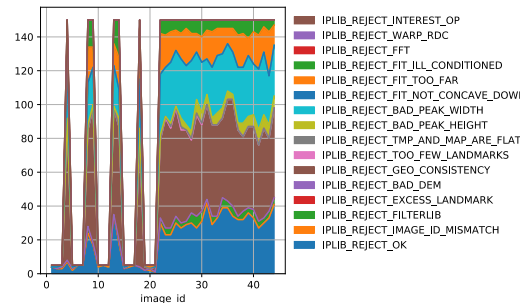


Figure 10. Example of coarse retry in PNV.

CONCLUSION

Results were presented from an extensive field test of the Mars 2020 Lander Vision System. The results clearly show that the LVS meets the required 40m position estimation requirement over an operational envelope expanded well beyond what is needed for flight. All of the objectives of the test were met with a statistically significant number of real-time LVS runs at representative altitudes. Many of the runs stressed position estimation and some resulted in execution of real-time fault responses. Finally, data was collected for off line assessment of the effect of vertical motion. Overall the flight LVS matched or exceed the performance of the prototype LVS³ indicating that the flight system design captured and then improved on the progress made in the technology development phase.

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